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ECL 240

A CASE STUDY ON SHAFT DESIGN

Large tunnels are being bored under Melbourne for the city's new underground railway. Another tunnel is being constructed to carry sewage to the city's latest sewage treatment plant. The tunnel-boring operations have revealed a lack of knowledge about the forces generated when cutting through various rock strata. A program of research into the mechanics of rock-cutting is therefore underway at the University of Melbourne, and the researcher, Gray Bailey, is designing a special machine for his experiments. He is a mining engineer so he seeks advice on the design of the main shaft of his machine from a mechanical engineer.

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The assistance of Mr. S.G. Bailey is gratefully acknowledged.

A CASE STUDY ON SHAFT DESIGN (A)

GRAY BAILEY HAS A PROBLEM

When an office door is open, the occupant of the office is available for consultation and does not mind being disturbed. This is an unwritten rule of academic life at the University of Melbourne. On the grey autumn morning on which this story begins, Ian McPherson's office door was open as he worked his way through the minutes of the various committee meetings he had attended during the previous month.

A bright young face peered around the doorway. "Hi," it said, "Are you the expert in shaft design?" Well, Ian was a senior member of staff in the Department of Mechanical Engineering at the University. He had designed some shafts and he had a copy of the latest edition of Professor Shigley's book* on his shelves, so he ventured a cautious affirmative.

"I'm Gray Bailey and I've got a problem in shaft design," said the visitor as he came into the office and sat down. McPherson pushed his academic papers to one side and prepared to listen to his visitor's story. Bailey explained that he had recently graduated in mining engineering and that he was now working on a research project for his Master's degree. He went on, "You've heard of the underground rail loop?" Who hadn't? Its escalating costs were the subject of periodical journalistic anger and taxpayers' laments. "And the South-eastern trunk sewer?" This was another rhetorical question because the best way of disposing of Melbourne's sewage had been the subject of extensive debate in the community. "Well, the engineers in charge of these projects are worried by the very wide variations in tunnelling rates achieved in similar rock strata. To plan their construction schedules and keep expenditures in line with budgets, they want to be able to predict tunnelling rates pretty accurately, much more accurately than they can at present. They also want data on wear of cutting tools in order to plan their maintenance shut-downs well in advance. Relevant information for local operating conditions is practically non-existent, so at their suggestion we have started work on a small project to investigate tool forces and wear rates in rock cutting. This will be a pilot study with a budget of $5,000 for the purchase of equipment. If our preliminary results are encouraging the research program will be extended and developed. I am responsible for the initial set of experiments and for the design and construction of a special test rig to be used in the research."

McPherson listened to Bailey's explanation with interest. "I know very little about rock cutting," he confessed. "What sort of equipment is used?"

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*Shigley, J.E. - "Mechanical Engineering Design," 3rd edition, McGraw-Hill, 1977.

"The tools which actually cut the rock are known as drag bits," Bailey replied. "A drag bit consists of a conical tungsten carbide tip brazed to a steel shank ; the steel is SAE 4140 quenched and tempered to give a yield strength of 1,760 MPa . Many different sorts of tool bit are used in practice, but the one we are interested in is shown in these photographs." A copy of the photographs is attached as Exhibit A-1. Bailey went on to explain that one of the contractors for the underground railway had purchased three tunnel-boring machines known as Alpine Miner F6A heading machines, see Exhibit A-2. In this type of machine, banks of drag bits are mounted on a rotating cutter head at the end of a projecting boom. During operation the boom is slewed so that the rotating cutter head ranges horizontally across the rock face.

"It seems to me that the cutting action at the rock face is very complex," commented McPherson. "How are you going to simulate it in your laboratory rig?"

"That's a good question," replied Bailey. "First of all, let me explain that because our research funds are limited, we have purchased second-hand a large horizontal boring mill which will be the basis of our test rig. It has adequate strength to withstand the cutting forces, and it will enable the cutting action to be simulated by traversing a slab of rock fixed to its work table past a rotating cutter head. In the test rig the cutter head will consist of a disc carrying a single tool and mounted on a shaft supported by bearings in the boring stay and face-plate of the machine. Anyway, all this is background information, what I want to discuss with you is the diameter of the main shaft in the test rig."

"O.K., what can you tell me about the shaft?"

"I've decided on the general layout of the machine as shown in this schematic drawing." A copy of Gray Bailey's drawing is attached as Exhibit A-3. "Some of the details have still to be worked out, but you can see the general dimensions. The tool bit will be mounted in a tool holder which in turn will be bolted to a disc on the shaft. We expect to use several different tool holders so that the tool bits can be presented at various angles of attack to the rock specimens."

"H'mm, I see. You have rather a long bearing span, no doubt to suit the layout of the horizontal borer."

Gray Bailey outlined his experimental program. The rock specimens would be prepared in the form of thin rectangular slabs, as shown in Exhibit A-3. An extensive series of tests was planned involving some hundreds of rock specimens. In each test the specimen would be mounted on a traversing table capable of being moved at speeds up to 10 cm s^{-1} in the longitudinal direction, i.e. parallel to the axis of the shaft. A single point cutting tool would be mounted on a tool holder on the shaft, but the details of this mounting had yet to be worked out. The

end of the tool would be conical in shape with an included angle of 90°, the tip being 30.5 cm from the center of the shaft. It was intended that the shaft rotate at 80 r.p.m. (8.38 rad s^{-1}), and the cutting tool carve out pieces of rock up to a maximum depth of 2 cm (see Exhibit A-3). The rock to be tested would be sandstone with a compressive strength of 21 MPa .

McPherson made notes rapidly as his visitor talked. Bailey had the facts at his fingertips, but needed prodding from time to time. "How will you drive the shaft?" McPherson asked.

"We have an electric motor available from another project, a 60 kW , 960 r.p.m., squirrel-cage machine. The drive to the shaft will be via a reduction gearbox, a hydraulic variable-speed device and a 1:1 horizontal chain-drive. The position of the sprocket on the shaft is shown in my diagram. Extrapolating from the results of other researchers I consider that the maximum tangential force on the tool during cutting is most unlikely to exceed 50 kN , and if you allowed say another 5% margin on this, I am sure your calculations would be very safe. 60 kW should be ample for the job."

Bailey showed signs of drying up, so McPherson prompted him again. "Is there anything else you can tell me?" he asked.

"Yes, there is one other thing. I have contacted the Commonwealth Steel Company and they have recommended for this application an alloy steel called 'Comsteel R4'. This is available in the form of solid bar up to diameters of 25 cm. It has an ultimate tensile strength of 1,000 MPa and an elastic limit of 740 MPa , so should have plenty of strength."

"I guess so. Do you mind if I ask once again if that is all you can tell me?" In McPherson's experience, clients are apt to forget or overlook important pieces of information unless you make every attempt to squeeze it out of them. But his direct question elicited nothing of interest. "Now you know as much as I do," Bailey reassured him. "All you have to do is tell me what diameter shaft I should use in my machine."

Ian McPherson sat back in his chair as Gray Bailey left his office. The information he had been given seemed very complete and he felt quietly confident he could solve the problem to the other's satisfaction. He cleared the routine papers off his desk and set to work.

QUESTIONS ON PART (A) :

1. How do you think Gray Bailey would describe the problem confronting him? How would he express what he wanted to accomplish?

2. How would Ian McPherson describe the problem confronting him? How would he express what he wanted to accomplish?

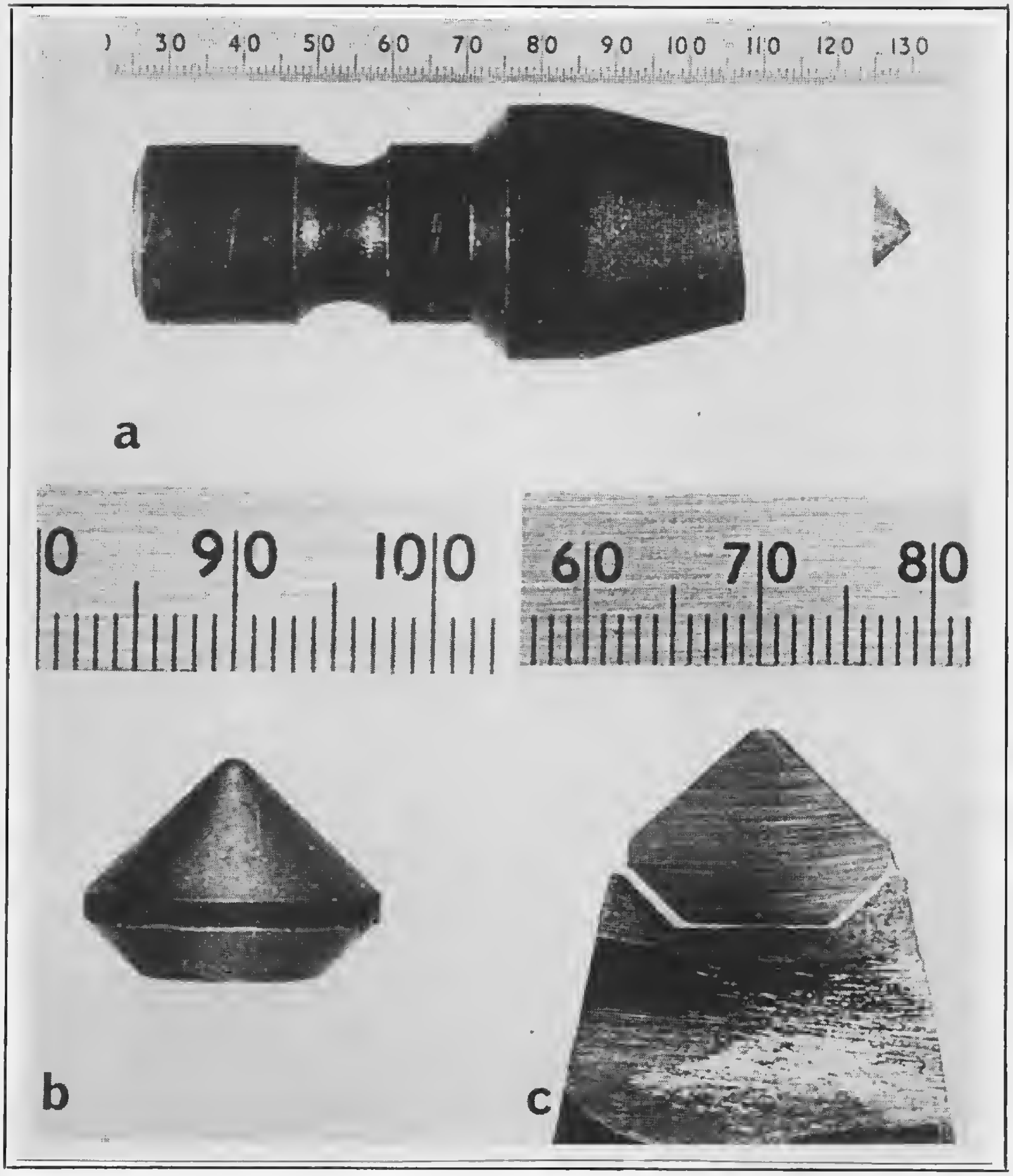
3. Comment on and explain any differences between your answers to Questions (1) and (2).

4. In one test it is possible that a number of parallel grooves will be cut in succession in one rock specimen. If the depth of cut is set at its maximum value of 2 cm , estimate the average power required to drive the shaft.

5. There is a mis-match between the source of power and the demand for it. The electric motor is capable of supplying 60 kW on a continuous basis, whereas the demand for power is intermittent. Explain what action should be taken to overcome this mis-match.

6. Draw a diagram showing the magnitude and direction of the forces and torques acting on the shaft. State clearly any assumptions you make.

7. Ian McPherson thought the information supplied by Gray Bailey "seemed very complete." Do you agree, or can you think of some relevant data which have not been provided?



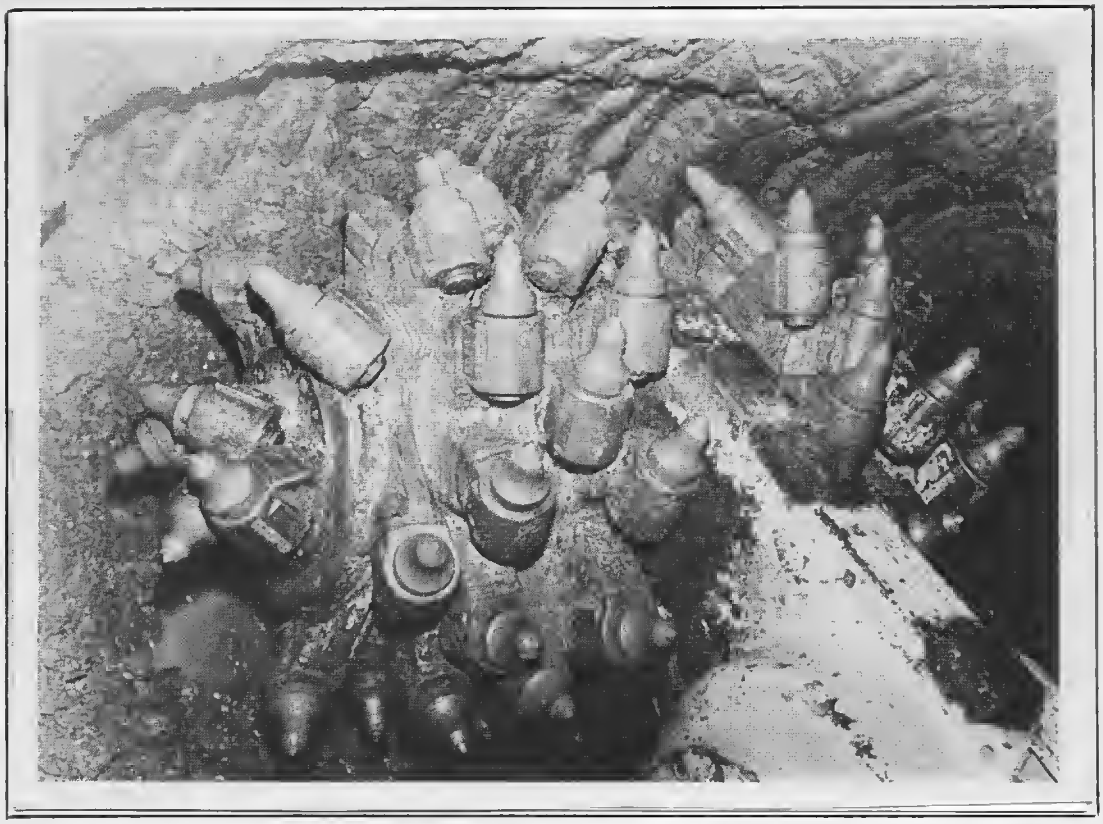
(a) Conical drag bit.

(b) Tungsten carbide tip.

(c) Transverse section showing tip brazed into steel shank.

Note : Scales show lengths in millimeters

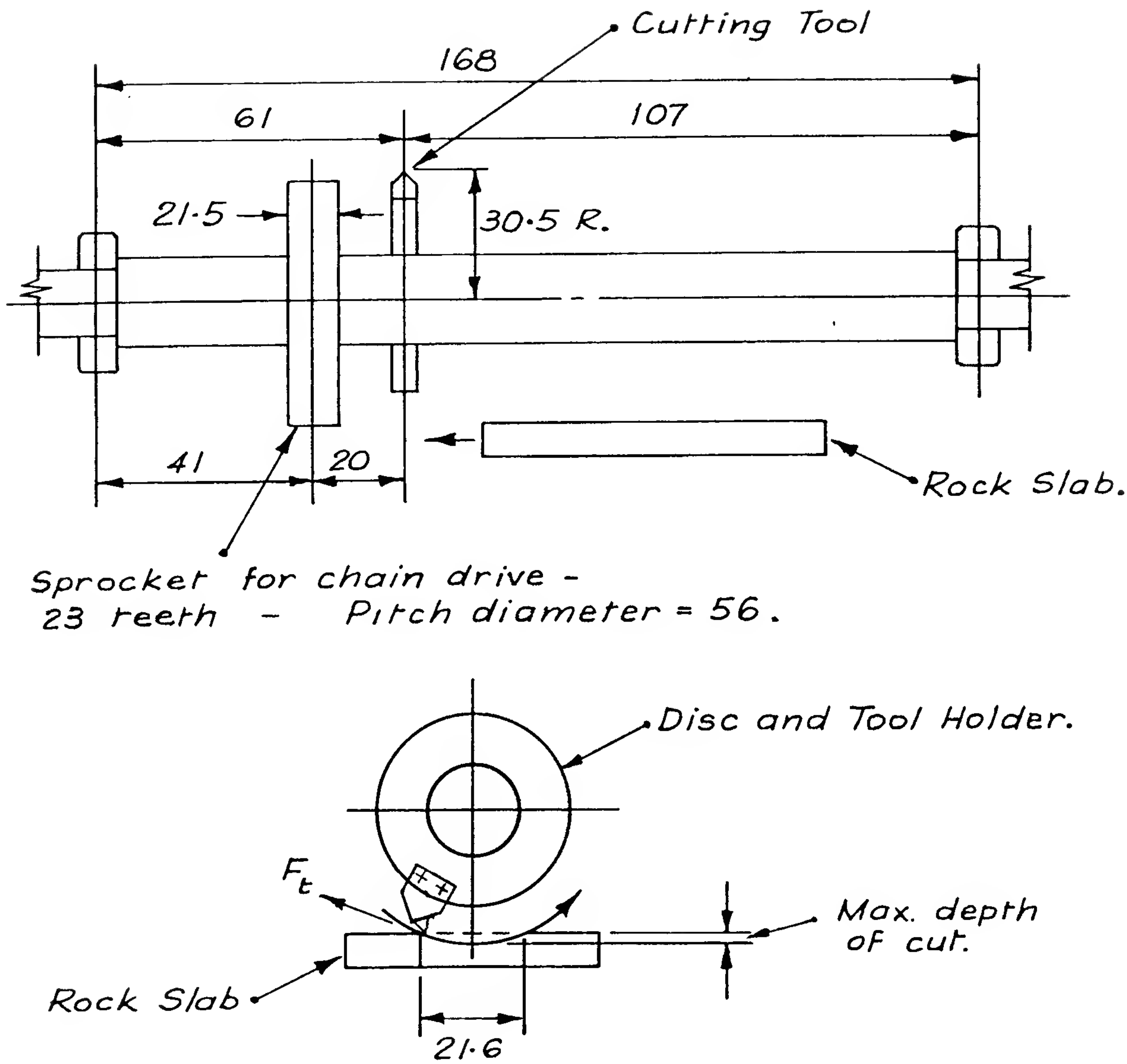
EXHIBIT A-1. CONICAL DRAG BIT



(a) External view

(b) Close-up of cutter head

EXHIBIT A-2. TUNNEL-BORING MACHINE



Notes: (1) F_t is tangential force on tool bit.
(2) End of tool bit is a conical surface with 90° included angle.
(3) Dimensions are in cm.

EXHIBIT A-3. SCHEMATIC OF SHAFT LAYOUT

A CASE STUDY ON SHAFT DESIGN (B)

IAN McPHERSON HAS SOME PROBLEMS

Ian McPherson started work by calculating the forces and torques acting on the shaft. Without bothering to think ahead into the design calculations. he was certain that this would provide him with essential information.

McPherson first calculated the maximum torque required as 52.5 x 0.305 = 16.0 kN m. He then turned his attention to the force on the shaft at the sprocket, but found that he did not know the direction of rotation of the shaft with respect to the position of the electric motor. There were two possibilities, shown in (a) and (b) of Figure B-1.

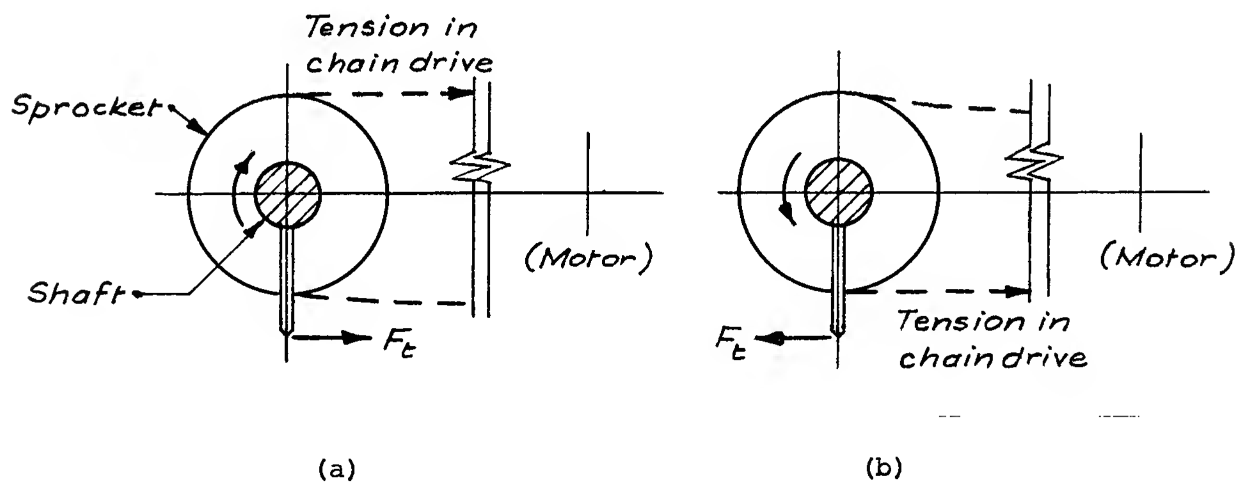


Figure B-1

A quick phone call to Gray Bailey established that the client had given no consideration to the position of the drive motor. Without giving the matter much thought McPherson decided to base his design on arrangement (a) because it represented a more adverse load condition on the shaft.

A roller chain transmits torque by engaging a series of teeth around the circumference of a sprocket. McPherson thought about the nature of this engagement. He wanted to determine the resultant force on the sprocket (and hence on the shaft), but this would depend on how the load

was distributed. Would it be distributed equally between all the teeth in engagement, or would inaccuracies in the manufacture of rollers and teeth lead to some teeth taking more of the load? He sought enlightenment on this matter from manufacturers' catalogues and several well-known texts on machine design, but in vain. After some minutes cogitation he concluded that the effects of any errors in manufacture would be small, and he proceeded on the assumption that the load would be equally shared between all the engaged teeth.

McPherson calculated F, the sum of the contact forces on the teeth in engagement on a pitch radius of 28 cm, as

$$F = \frac{30.5}{28} \times 52.5 = 57.2 \text{ kN} .$$

The resultant force on the sprocket (see Appendix) was then

$$F_B = \frac{2}{\pi} F = 36.5 \text{ kN}$$

in the vertically upwards direction. Could one assume that F_B acted at a point? Strictly speaking, no - because the width of the sprocket hub was around 12 cm. However, he assumed that F_B was a point load because it was computationally convenient, and because it would lead to higher computed bending moments than if F_B were assumed to be uniformly distributed over the width of the sprocket. With respect to the bearing reactions, it seemed entirely reasonable to take them as point loads too. Construction of the free body diagram for the equilibrium of the shaft was now well in hand.

QUESTIONS ON PART (B) :

A Note on Terminology :

The questions below refer to "decisions," "assumptions" and "estimates." These three concepts are intended to refer to three separate and distinct mental activities on the part of the designer.

In the design of an engineering component, *decisions* are made concerning the performance required from the component and concerning its size, shape and material of construction.

Mathematical models are used to predict the performance of engineering components. *Assumptions* are made by the designer in order to construct models which are both valid representations of physical phenomena and computationally convenient.

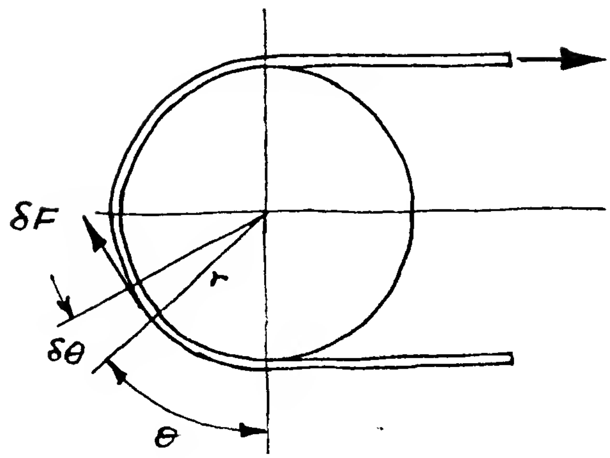
It is often found that the quantitative data required as inputs to these models are either not known or known only approximately. In such cases the designer has to make numerical *estimates*.

1. List the decisions and assumptions made by Ian McPherson in Part (B). Are they the same as you made in answering question (6) in Part (A)? Comment on any differences. Has Ian McPherson generated enough information to construct the free body diagram or are there further decisions, assumptions or estimates to be made?

2. Once the forces and torques acting on the shaft have been determined, what does McPherson then have to do to decide on a suitable shaft diameter? List the steps in his procedure, and highlight any decisions, assumptions or estimates he will have to make.

3. Make what calculations you consider appropriate and decide on the shaft diameter you would recommend for this application.

APPENDIX TO PART (B) : EXTRACT FROM IAN McPHERSON'S NOTEBOOK.



Consider the limiting case where the number of sprockets is infinitely great.

The tangential force per unit length of circumference is denoted f and is assumed to be constant.

On an element of the circumference of length $r\,\delta\theta$ which subtends an angle $\delta\theta$ at the centre of the sprocket the force on the sprocket is

$$\delta F = f\,r\,\delta\theta$$

The resultant force on the sprocket in the vertically upwards direction is

$$F_B = \int_0^\pi \delta F \sin\theta \, d\theta$$

$$\therefore \quad F_B = f r \int_0^\pi \sin\theta \, d\theta = 2 f r .$$

The resultant force in the horizontal direction is

$$f r \int_0^\pi \cos\theta \, d\theta = 0$$

The torque transmitted $= F \times r$

where $\qquad F = \pi r f$

$$\therefore \quad f = \frac{F}{\pi r}$$

$$\therefore \quad F_B = \frac{2}{\pi} F = 0.637\,F.$$

A CASE STUDY ON SHAFT DESIGN (C)

IAN McPHERSON MAKES A RECOMMENDATION

The velocity ($\underset{\sim}{v}$) of the tip of the cutting tool with respect to the workpiece has components in three directions - tangential, axial and radial, as indicated by $\underset{\sim}{v}_t$, $\underset{\sim}{v}_a$ and $\underset{\sim}{v}_r$ in Figure C-1 .

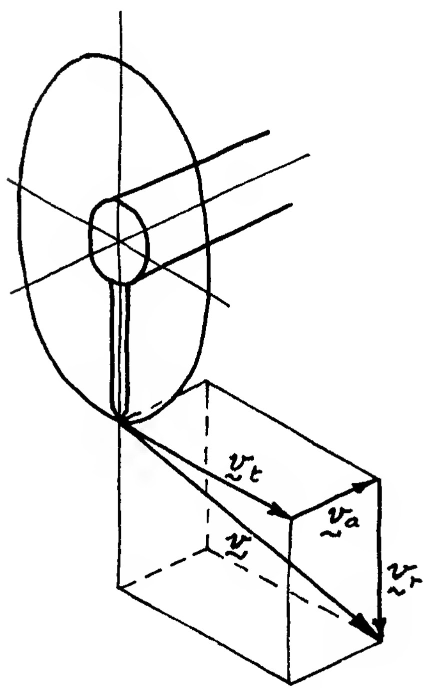


Figure C-1

In his mind's eye, McPherson visualized the action of the cutting tool as also being three-dimensional, with axial and radial components of the cutting force (F_a and F_r respectively) as well as the tangential component F_t .

He wondered how to estimate F_a and F_r . After all it wouldn't be until Gray Bailey's machine was built and some tests carried out that worthwhile information on these force components would be available. With respect to F_a , the only thing he could think of doing was to take F_a as the same proportion of F_t as v_a was of v_t . This gave

$$F_a = \frac{10}{256} \times 52.5 = 2 \text{ kN near enough.}$$

It seemed clear that F_a would give rise to quite small bending and axial stresses compared to those due to the other loads present. McPherson therefore dropped F_a from his calculations. To get some leverage on F_r , he resorted to an analogy with metal cutting. From

chapter 3 of "Machining of Metals" by Armarego and Brown*, it appeared that F_r was quite appreciable in metal cutting, perhaps 30% to 40% of F_t . With no better information available and recognizing that the properties and structure of sandstone were quite different to those of metals, he estimated F_r to be 16 kN .

McPherson could then draw a diagram showing the peak loads on the shaft. This he did, as shown in Figure C-2 where the stations A , B , C and D represent respectively the left-hand bearing, the sprocket, the cutting tool and the right-hand bearing.

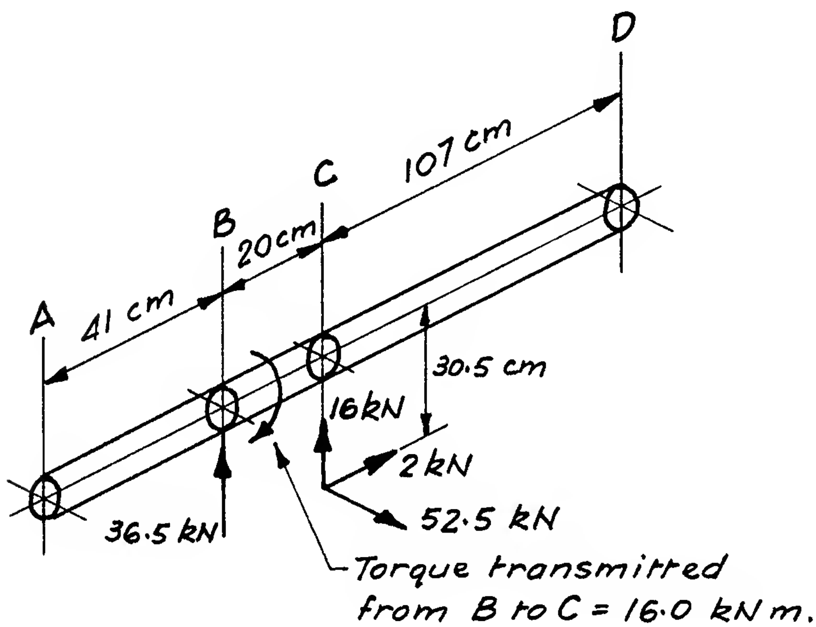


Figure C-2

Some preliminary figuring convinced McPherson that the most highly stressed section of the shaft was at station C . He therefore calculated bending moments for this station, firstly in the horizontal plane (M_H , see Figure C-3), then in the vertical plane (M_V) .

$$M_H = \frac{0.61 \times 107 \times 52.5}{168} = 20.4 \text{ kN m}$$

* Armarego, E.J.A. and Brown, R.H. - "Machining of Metals," Prentice-Hall, 1969.

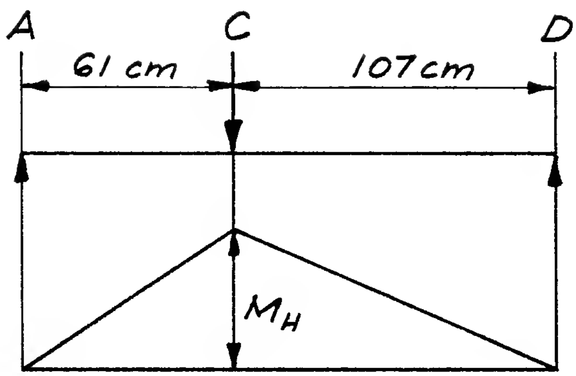


Figure C-3

In a similar manner, M_V was calculated.

$$M_V = \frac{0.61 \times 107 \times 16}{168} + \frac{87}{107} \times \frac{0.41 \times 127 \times 36}{168} = 15.3 \text{ kN m}$$

The resultant bending moment at C was

$$M = \sqrt{M_H^2 + M_V^2} = 25.5 \text{ kN m}$$

McPherson assumed that the angular acceleration of the shaft would be small, and that at every instant the shaft would be in equilibrium with the torque (T) applied at the sprocket equal to that required to drive the cutting tool. He sketched a graph showing the variation of M and T with time (Figure C-4), in which M_m and T_m denoted mean values and M_a and T_a the amplitude of variation around the mean values.

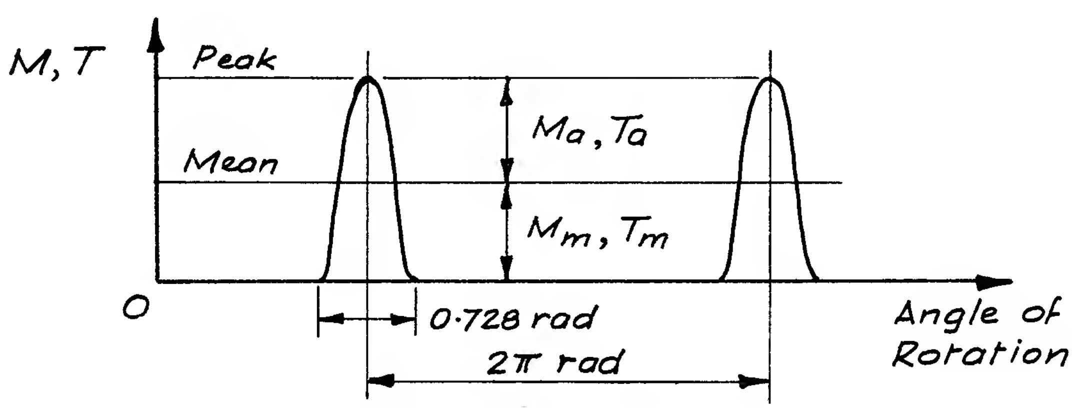


Figure C-4

There are a number of different equations for designing shafts to resist fatigue failure. McPherson referred to Baumeister and Marks' "Mechanical Engineers' Handbook"* and found the following design equation applicable to the conditions of his problem.

$$d = 2.17 \sqrt[3]{n} \left\{ \sqrt{\left(\frac{M_m}{S_u} + K_{tf} \frac{M_a}{S_e} \right)^2 + \frac{3}{4} \left(\frac{T_m}{1.33 S_y} + K_{tfs} \frac{T_a}{S_e} \right)^2 } \right\}^{1/3}$$

McPherson realised that the magnitudes of some of the quantities on the right-hand side of this equation were unknown and would have to be estimated. He reviewed the situation.

$$M_m = M_a = 12.75 \text{ kN m}$$

$$T_m = T_a = 8.0 \text{ kN m}$$

S_u = ultimate tensile strength.

He decided to stick with Gray Bailey's suggested alloy steel for which $S_u = 1{,}000$ MPa and yield strength $S_y = 740$ MPa.

S_e = endurance limit. The manufacturer's catalogue did not supply this information. On the basis of Figure 5-13 on p.181 of Shigley's book McPherson estimated S_e as 480 MPa, slightly on the conservative side of Shigley's recommendation that S_e be taken as $0.5\ S_u$. In any case Bailey's test machine would only operate for some tens of thousands of stress cycles, so to use the endurance limit which corresponded to an infinite fatigue life was very conservative.

K_{tf} and K_{tfs} are fatigue strength reduction factors due to the presence of stress concentrations at shaft shoulders and keyways. Details of the attachment of the sprocket and cutting tool to the shaft head had not yet been worked out. For K_{tf} McPherson first estimated a likely stress concentration factor of 1.5, being guided by the data on pages 5-9 and 5-10 of Baumeister and Marks. In the equation

$$K_{tf} = q\,(K_t - 1) + 1$$

q is the notch sensitivity of the material, but its value for Comsteel R4 was not known. After referring to the data in Figure 5-19 on

* Baumeister, T. and Marks, L.S. (editors) - "Mechanical Engineers' Handbook," 7th edition, McGraw-Hill, 1967, p.8-67.

p.195 of Shigley's book, McPherson estimated q as 0.90 . This gave

$$K_{tf} = 0.9\ (1.5 - 1) + 1 = 1.45$$

which he rounded off to 1.5 .

He thought that K_{tfs} would be slightly higher than K_{tf}, so estimated it as 1.7 . The design equation then reduced to

$$d = 8.58\ n^{1/3}\ \text{cm} .$$

He felt very unsure about the value he should take for the factor of safety n , so he graphed d as a function of n , as shown in Figure C-5 . This helped him visualize the magnitudes of the quantities involved and the rate of change of d with respect to n . From the graph and from his experience of other shaft designs McPherson felt that a diameter of 14 cm would be safe, as a fatigue failure seemed very unlikely, with a factor of safety of just over 4 .

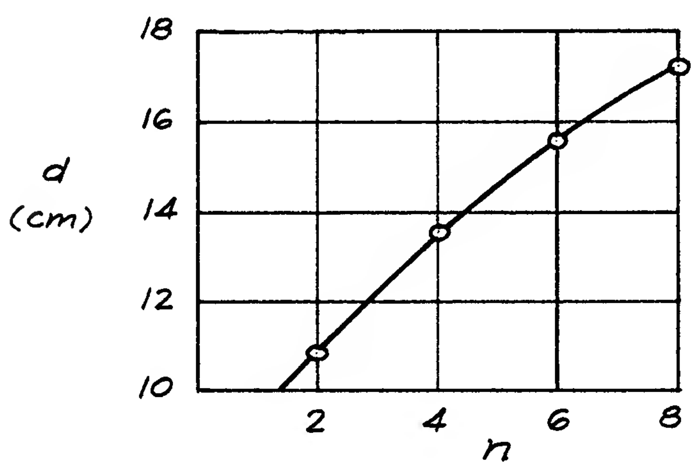


Figure C-5

"What now?" he asked himself. He turned his attention to the next most obvious mode of failure - excessive deflection of the shaft. Bailey had said nothing about this in their initial discussion, so McPherson phoned him and the following conversation ensued.

"Gray? Ian McPherson here. I'm working on your shaft design and I've just realized that I forgot to ask you to specify the maximum allowable deflection."

Bailey sounded surprised. "Will the shaft deflect?" he asked, "I hadn't really thought about it."

"Of course it will. You've got quite high loads and a long bearing span. I feel sure that deflection will be significant."

"Will it? Oh well, I'll leave it to you. You're the expert."

"H'mm", McPherson said to himself, "there's more to this shaft problem than meets the eye." After further thought he came to the following conclusions. The horizontal deflection of the shaft at B would be limited by the need to maintain the center distance of the chain-drive close to its initial value to ensure accurate engagement of the rollers in the sprockets. The vertical deflection at C would be limited by the need to maintain accurate depths of cut during testing. Depth of cut was an important experimental variable, and it had to be possible to set up the machine to cut slabs to a depth which was known to good accuracy. In McPherson's judgement neither of these deflections should exceed 0.5 mm, and he decided to base his design calculations on this figure.

He considered the horizontal deflection at B (δ_B) first, and used the well-known result for a simply supported beam, see Figure C-6.

$$\delta_B = \frac{Pbx}{6EI\ell}(\ell^2 - b^2 - x^2)$$

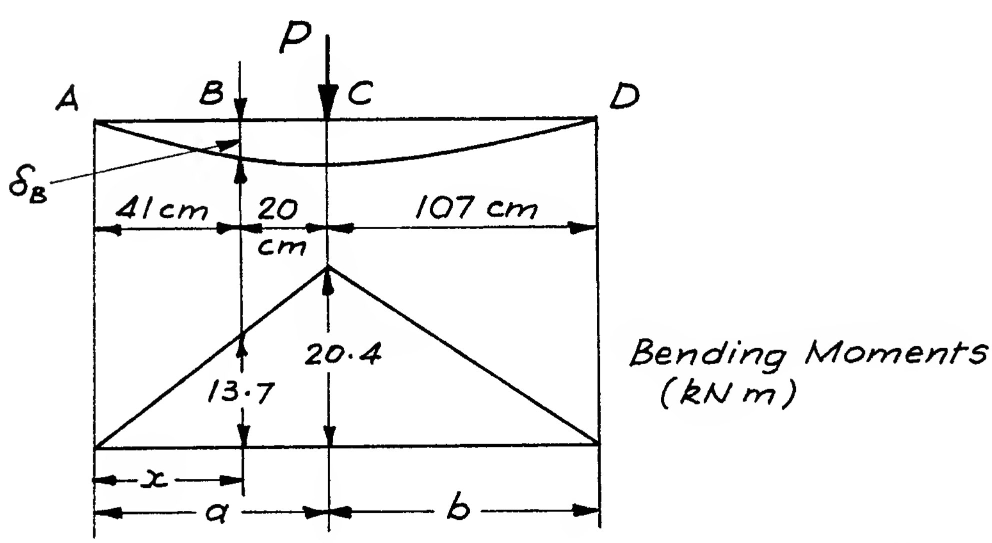


Figure C-6

Since $\delta_B \leqslant 0.0005$ m, substitution in this equation for deflection yields

$$I = \frac{\pi d^4}{64} \geqslant 0.354 \times 10^{-4} \ m^4$$

whence $$d \geqslant 16.4 \ cm \ .$$

This seemed a reasonable result to McPherson. It ignored any changes in diameter or shoulders on the shaft for locating bearings or attachments, but their effect was likely to be small in his judgement.

The vertical deflection at C (δ_C) was the sum of the deflection due to F_r and the deflection at C due to the force of 36.5 kN at B. McPherson calculated that

$$\delta_C = \frac{1.893}{I} \times 10^{-8} \leqslant 5 \times 10^{-4}$$

$$\therefore \quad I = \frac{\pi d^4}{64} \geqslant 0.379 \times 10^{-4} \ m^4$$

whence $$d \geqslant 16.7 \ cm \ .$$

Allowing a little extra margin for safety, he decided provisionally to recommend a shaft of 18 cm diameter.

McPherson then checked his calculations and asked himself if there was anything else he should do before he got in touch with Gray Bailey. Looking once again at the layout drawing, he realized that the shaft would be quite heavy. He computed its weight as 3.3 kN, a not insignificant load but not big enough to force him to repeat the design calculations. The shaft's first critical speed was way above its operating speed so that was no problem. He decided to stick with his recommendation of 18 cm diameter, but there were two matters to which Bailey's attention should be drawn. Firstly, the bending moments on the shaft could be significantly reduced by moving the drive sprocket closer to the left-hand bearing. Secondly, because the shaft design was controlled by deflection and not by stress, Bailey should consider using plain mild steel; an alloy steel was not required.

Everything seemed in order, yet McPherson could not shake off the nagging feeling that the design could be improved. He remembered how he spurred his students on by repeating the slogan, "There must be a better way!" No inspiration came, so he decided to sleep on the matter and confer with Gray Bailey the next morning.

QUESTIONS ON PART (C) :

1. Derive the equation McPherson found in Baumeister and Marks for designing shafts to resist fatigue failure.

2. List the decisions, assumptions and estimates made by Ian McPherson in Part (C). Discuss the judgements he made and explain whether or not you think they are reasonable in the light of the uncertainties he faced. Does his final recommendation of 18 cm diameter provide a sufficient margin of safety in your opinion or is it over-cautious?

3. Critically review all the major design decisions taken so far. See whether you can devise a better way of doing what Gray Bailey wanted to do.

4. In this case the work of the engineering designer has been described mainly by use of the English language. The designer has generated and processed information in a number of different ways : deciding, assuming, representing, estimating, calculating. This suggests that we examine and display his activities in visual form. Construct a chart or network to show the sequence of information processing operations and the flows of information between them. Which parts of the network are amenable to computer aid, perhaps in an interactive mode? Formulate the requirements for an interactive computer program in shaft design.

A CASE STUDY ON SHAFT DESIGN (D)

GRAY BAILEY DECIDES

At a meeting with Bailey the next morning McPherson submitted his recommendations and outlined the calculations he had performed. He then questioned Bailey once again about the test rig. A Socratic dialogue ensued.

"What you really want to do is rotate a cutting tool?"

"Yes."

"So we have to provide an axis about which the cutting tool can rotate?"

"Yes."

"And a method of applying a torque to the tool?"

"Yes."

"And you can mount the sprocket close to the cutter disc?"

"Yes."

"Well, why don't you do something like this?" and McPherson quickly sketched the arrangement shown in Figure D-1 .

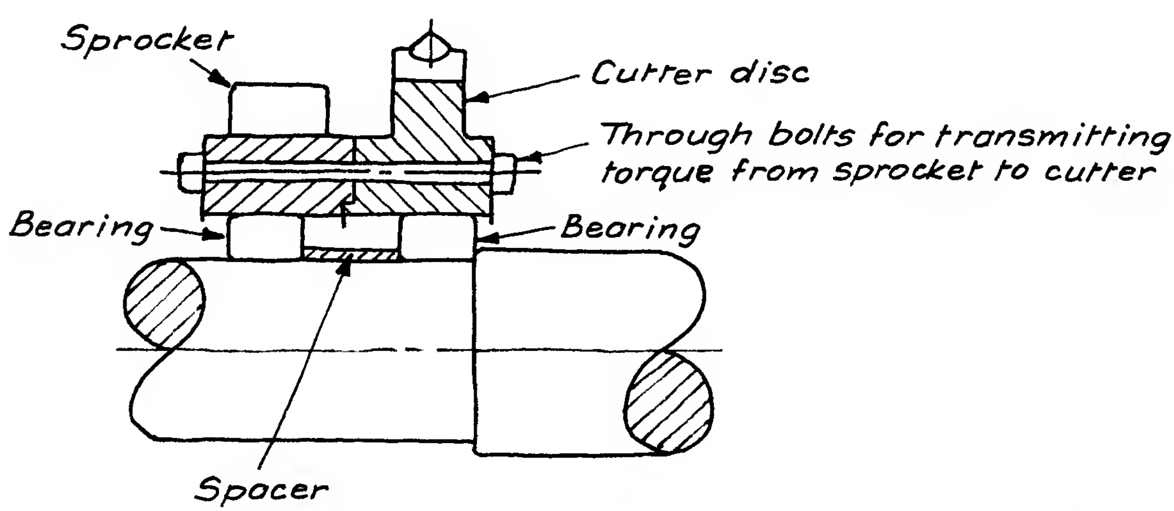


Figure D-1

"Why, that's a great idea!" Bailey was enthusiastic. "The shaft doesn't transmit any torque, it doesn't rotate, it's subject only to bending. Its ends can be rigidly attached to the horizontal borer in some way. I'll work out the details immediately."

Subsequently, Gray Bailey decided to stick with the shaft diameter of 18 cm as far as he was able. The expert had recommended this figure, the expert knew more about shafts than he did so he felt very reluctant to make a change. The need to provide locating shoulders for the sprocket and cutter disc bearings led him to reduce the shaft diameter to the left of the sprocket from 18 cm to 15.5 cm. Bailey did not change his original decision to use the R4 alloy steel because he liked to think he had this additional margin of safety up his sleeve. In his scale of values it was more important to have a test rig which worked than to try and save about $500 in the manufacture of a critical component. He held to this view even though his total budget for the purchase of materials and equipment was $5,000. A picture of the test rig as finally built is appended as Exhibit D-1 .

QUESTION ON PART (D) :

1. Design the components shown in Figure D-1 in detail. Select suitable bearings, and take suitable precautions to ensure that your design is fail-safe so that both the shaft and the chain-drive are protected from any excessively large cutting forces.

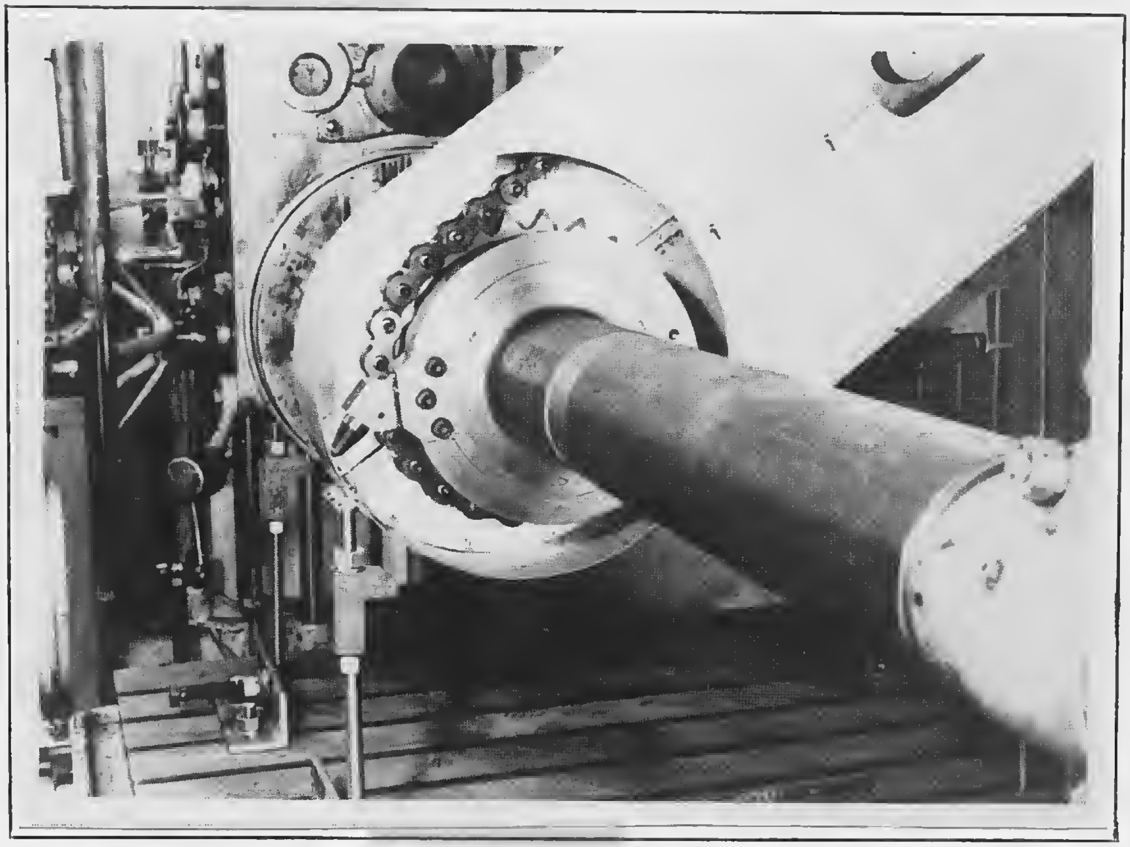


EXHIBIT D-1. CLOSE-UP OF TEST RIG SHOWING CUTTING TOOL AND CHAIN-DRIVE.

INSTRUCTORS' NOTES

This is a case in mechanical engineering design. The problem appears simple, just to determine a single dimension, a shaft diameter. But appearances are deceptive ; the material presented has much wider implications and can be used to study a number of important matters in engineering education. By drawing attention to these matters the following notes are intended to help instructors make effective use of the case.

(1) Relationship between designer and client

The communications between the client (Gray Bailey) and the consultant (Ian McPherson) are brief, but what they say and do is sufficient to reveal the different frames of reference in which they view the problem. Bailey wants a machine which will work satisfactorily and give him the desired experimental results ; he has not formulated his technical requirements in any detail, and in fact it remains for McPherson to do this. In real life McPherson is rather a cautious chap and this tends to be reflected in the advice he gives. Bailey on the other hand is the one who has to make the decision and take the responsibility of committing relatively scarce research funds. McPherson can afford to play it safe, but Bailey has to worry about the costs incurred by providing an excessive margin of safety. Hopefully, these points can be brought out in class discussions of questions (1), (2) and (3) at the end of Part (A) and question (2) at the end of Part (C).

(2) The designer's approach to his work

Although McPherson is an experienced engineer, the full ramifications of the problem are not immediately apparent to him. It is fair to say that he adopts a step by step approach. He first considers the loads on the shaft, and when they have been calculated he investigates the design of the shaft for stress. When that step has been completed he goes on to consider the question of shaft deflection. Although the initial information "seemed very complete" to him, McPherson finds that he needs additional information from Bailey from time to time. With respect to shaft deflection he raises an important technical matter to which his client has given no thought. After all, Bailey was not an expert and had not appreciated that the shaft could deflect by a significant amount. Question (7) at the end of Part (A) and questions (1) and (2) at the end of Part (B) are intended to draw attention to this facet of the case.

Question (3) at the end of Part (C) emphasizes the importance of self-awareness on the part of the designer, the capacity for continually evaluating his own work and not being content to accept results which appear on the surface to be quite satisfactory.

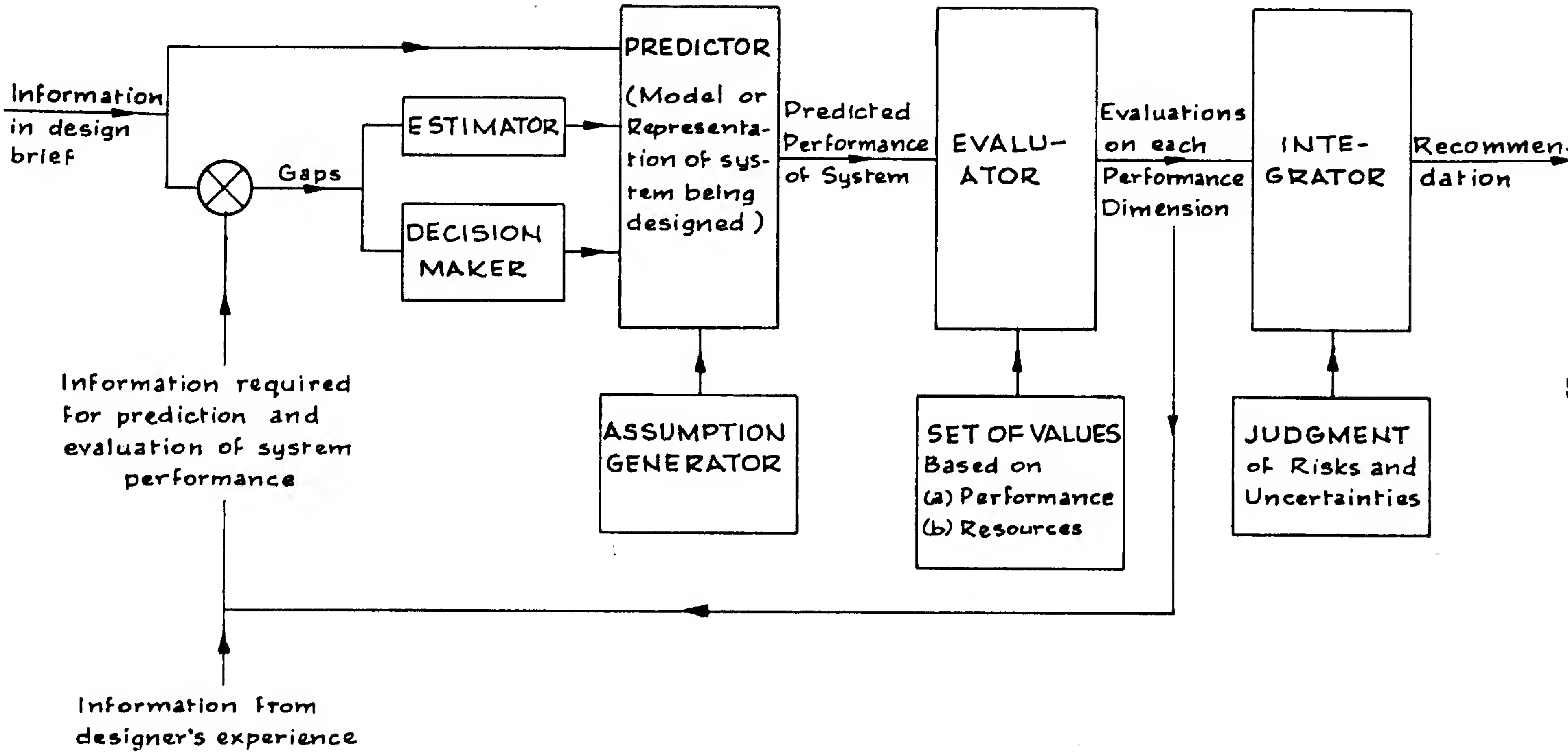


Fig. 2. Flow Chart of Information Flows in Case.

Explanation of Symbols used in Fig. 1.

D_i = Decision

A_i = Assumption

R_i = Representation, mathematical model

E_i = Estimate

I_i = Item of information in the flowgraph.

The D_i's , A_i's , R_i's , E_i's and I_i's are numbered in order, and explanatory notes in the flowgraph indicate their nature.

In addition the following symbols are used.

d = calculated shaft diameter

F = factor of safety

F_a = axial force on cutting tool

F_r = radial force on cutting tool

I_R = information on resources available for manufacture of shaft

I_{OUT} = final output of information

INT = denotes integrating decision where the designer draws on all the information available to him about shaft performance and costs

K_{tf}, K_{tfs} = stress concentration factors

S_e' , S_e = endurance limit of shaft material under laboratory and working conditions respectively

δ = calculated shaft deflection.

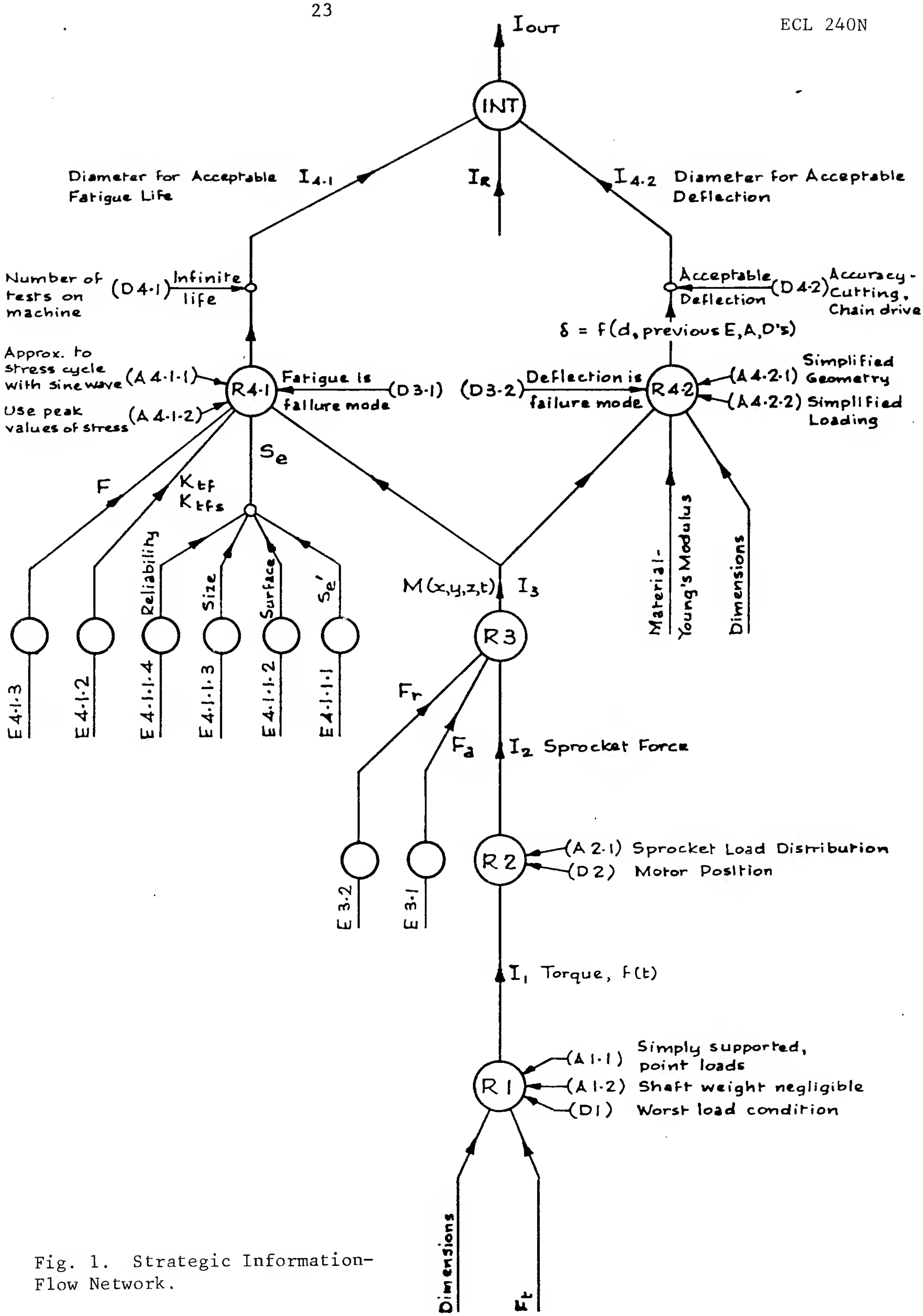


Fig. 1. Strategic Information-Flow Network.

(3) Information Flows

The note on terminology at the end of Part (B) identifies the different ways in which the designer generates and processes information. While working on his problem McPherson was not consciously aware of these various information processing operations and did not separately identify them in his own mind, he just got on with the job at hand. At the end of Part (C) of the case and with the benefit of hindsight, we can construct a network representing his design strategy, a network in which the nodes are information processing operations and the links between nodes are transfers of information. A convenient acronym for such a network is SIN - strategic information - flow network. The SIN for this case is shown in Fig. 1 near the end of these notes.

It is also possible to represent McPherson's design activity in a more general way by means of the flow chart shown in Fig. 2. Figs. 1 and 2 are relevant to question (2) at the end of Part (B) and question (4) at the end of Part (C). These questions are intended to deepen students' understanding of the nature of engineering design, and to introduce them to the computer and its potential for augmenting the work of the designer in engineering.

(4) Engineering Judgement

Engineering judgement is a very general and all-embracing concept. Question (1) at the end of Part (B) and question (2) at the end of Part (C) are intended to give a clearer picture of what it encompasses. The case describes how McPherson overcame the uncertainties facing him to arrive at a final recommendation. Whether his judgement was sound in every particular can be the subject of class discussion. The assumption in Part (B) of a uniform distribution of load over the sprocket teeth in engagement might very well be questioned. Students of the case could investigate the consequences of making alternative assumptions, perhaps making the extreme assumption that all the load acts on one tooth.

(5) Machine Design

The case provides the opportunity of asking students a number of questions in conventional machine design, and the instructor can use the case for this purpose if he wishes. The following questions are in this category :

Part (A) - Questions (4), (5) and (6)

Part (B) - Question (3)

Part (C) - Question (1)

Part (D) - Question (1)